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Invited Review

A review of crust and upper mantle structure beneath the Indian subcontinent

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ABSTRACT

This review presents an account of the variations in crustal and upper mantle structure beneath the Indian subcontinent and its environs, with emphasis on passive seismic results supplemented by results using controlled seismic sources. Receiver function results from more than 600 seismic stations, and over 10,000 km of deep seismic profiles have been exploited to produce maps of average crustal velocities and thickness across the region. The crustal thickness varies from 29 km at the southern tip of India to 88 km under the Himalayan collision zone, and the patterns of variation show significant deviations from the predictions of global models. The average crustal shear velocity (Vs) is low in the Himalaya–Tibet collision zone compared to Indian shield. Major crustal features are as follows: (a) the Eastern Dharwar Craton has a thinner and simpler crustal structure crust than the Western Dharwar Craton, (b) Himalayan crustal thickness picks clearly follow a trend with elevation, (c) the rift zones of the Godavari graben and Narmada–Son Lineament show deeper depths of crust than their surroundings, and (d) most of the Indian cratonic fragments, Bundelkhand, Bhandara and Singhbhum, show thick crust in comparison to the Eastern Dharwar Craton. Heat flow and crustal thickness estimates do not show any positive correlations for India.

Estimates of the thickness of the lithosphere show large inconsistencies among various techniques not only in terms of thickness but also in the nature of the transition to the asthenosphere (gradual or sharp). The lithosphere beneath India shows signs of attrition and preservation in different regions, with a highly heterogeneous nature, and does not appear to have been thinned on broader scale during India's rapid motion north towards Asia. The mantle transition zone beneath India is predominantly normal with some clear variations in the Himalayan region (early arrivals) and Southwest Deccan Volcanic Province and Southern Granulite Terrain (delayed arrivals). No clear patterns on influence on the mantle transition zone discontinuities can be associated with lithospheric thickness. Over 1000 anisotropic splitting parameters from SKS/SKKS phases and 139 using direct S waves are available from various studies. The shear-wave splitting results clearly show the dominance of absolute-plate-motion related strain of a highly anisotropic Indian lithospheric mantle with delay times between the split S phases close to 1 s. There are still many parts of India where there is, at best, limited information on the character of the crust and the mantle beneath. It is to be hoped that further installations of permanent and temporary stations will fill these gaps and improve understanding of the geodynamic environment of the Indian subcontinent.

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1. Introduction

The Indian subcontinent is formed of a mosaic of various Precambrian tectonic provinces, with stable shields in peninsular India to actively deforming collision belts in the Himalaya, and has experienced extensive volcanism and rifting. India lies on a fast moving plate and has covered a large distance since its separation from the other components of Gondwana (ca 130 Ma). The influence of the fast drift on the stability of cratons, and removal of lithospheric roots are key issues which are much debated (Kumar et al., 2007), but as yet are not fully understood.

In the century since the detection of the Mohorovičić discontinuity (Mohorovičić, 1910) from earthquake observations, both controlled source and passive seismic studies have made impressive advances in understanding the nature of the crust and uppermost mantle (Prodehl et al., 2013). Multiple facets of seismic wave propagation can be brought to bear on the structure of the Earth's interior, and help to resolve the key issues related to evolution and nature of the continental crust and upper mantle. To date there have been only limited attempts to provide a full picture of the Indian crust and upper mantle. There have been reviews of heat flow (Roy and Rao, 2000) and deep seismic sounding studies (Kaila and Krishna, 1992; Reddy and Rao, 2013). However, the full range of available information on the crust and upper mantle available from passive source studies have not previously been exploited.

The foundation stones of seismology in India were laid by the pioneering works of Dr. T. Oldham and Dr. R. D. Oldham, the father–son duo. The great Shillong earthquake of 12th June, 1897 is well documented and reported in the works of Oldham (1899). This deadly Shillong earthquake achieved the maximum intensity XII on MM scale (Richter, 1958), and provided the impetus for a series of initiatives to install seismographs in India to monitor earthquakes. The first few installations were made of Milne's self registering seismographs in Alipore (Calcutta, now Kolkata), Colaba (Bombay, now Mumbai) and Madras (now Chennai) (Tandon, 1992). An Omori-Ewing seismograph was installed in Simla as a response to the great Kangra earthquake of 5th April, 1905. In the years from 1929 to 1930, the country was equipped with a few more Milne-Shaw seismographs, initially installed at Colaba observatory Mumbai, then Bombay and later at few more places in Agra, Calcutta, Hyderabad and Kodaikanal. In the early 1960s five World Wide Standard Seismograph Network (WWSSN) stations were installed at various places across the country following the recommendations of Berkner (1959). After the devastating Latur earthquake of September 30th, 1993 the India Meteorological Department upgraded ten of its observatories to the standard of Global Seismograph Network, and later complemented this network with 14 more broadband stations during 1999–2000. At present the India Meteorological Department runs nearly 80 seismic stations in the national network, supplemented by various temporary networks operated by other organizations. Temporary and permanent networks in different parts of India have been operated by the National Geophysical Research Institute, Indian Institute of Technology Bombay, Wadia Institute of Himalayan Geology, Tezpur University and the Institute of Seismological Research. The National Geophysical Research Institute has established more than 200 broadband seismic stations at various points of time, and so plays a major role in passive source seismology in India.

Deep seismic probing of Indian crust, started in 1972 with refraction/wide-angle reflection work, but subsequently was dominated from the early nineties by deep seismic reflection. A good deal has been achieved (Kaila and Krishna, 1992), with more than 10,000 km of profiles carried out in various experiments using controlled sources. A major supplementary source of information on Indian structure comes from the use of seismic receiver functions exploiting the recordings of distant earthquakes. Receiver functions provide a tool to map the Earths response beneath a single three-component seismic station, and extract information on the seismic discontinuities at depth from the conversions and reverberations associated with the main seismic phases. The first receiver functions for the Indian region used data from the Hyderabad station (HYB) in India, using P-to-s converted waves (Gaur and Priestley, 1997). Since then the role of receiver functions in determining crust and upper mantle discontinuities (Moho, lithosphere–asthenosphere boundary, mantle transition zone discontinuities 410 and 660) has been routine practice. Further information comes from seismic anisotropic studies using SKS/SKKS phases and heat flow that provide links to help understand both geodynamics and structure. The present work presents as a complete picture of the Indian crust and upper mantle as possible, compiled from various sources with emphasis on passive source seismic datasets. We synthesize results from seismic studies, heat flow and seismic anisotropy to develop a comprehensive map of the properties of the crust and upper mantle beneath the Indian subcontinent, with links into the Himalaya and Tibet to provide a wider perspective and understanding of the whole region.

2. Tectonic setting

The major tectonic units of peninsular India comprise Precambrian terranes (Fig. 1). A vast region in between the peninsula and the actively deforming regions of Himalaya and Tibet is covered by quaternary sediments. These sediments, mainly of Himalayan origin, form the Indo-Gangetic plains with very thick sedimentary deposits (>8 km).

The western central portion of India is overlain by flood basalts known as the Deccan Traps or the Deccan Volcanic Province (DVP). The Indian plate has crossed over various hotspots (Rèunion, Krozet, Kergulean and Marion) in its rapid transit to the north. The passage over the Rèunion hot spot (Chenet et al., 2007) has led to a major volcanic event, which resulted in creation of the Deccan Traps. The flood basalts are of considerable thickness (>1.5 km) and cover a region of more than 500,000 km^2. Recent results from Deep Scientific Drilling in the Koyna region provide direct estimates of a 931 m thick basaltic layer followed by a paleoregolith of thickness of 4 m (Rao et al., 2013). The Cambay Rift (CBR) divides the Deccan Traps into two distinct units, one in the northwest and the other in the southwest. The Cambay Rift is filled with tertiary sediments, and is interpreted as a failed rift formed due to extensional tectonics.

The other major rift systems are the Godavari Graben (GG) and the Mahanadi Rift (MHR), which are passive in nature but which have left